SEISMIC DATA LABORATORY

QUARTERLY TECHNICAL SUMMARY REPORT

15 July 1965

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UED EARTH SCIENCES DIVISION
TELEDYNE, INC.

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SEISMIC DATA LABORATORY
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SUMMARY REPORT

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I. INTRODUCTION

This report, the first quarterly technical summary report issued by the SDL, covers the period April 1965 through June 1965. Previously, reports of this type were issued on a semi-annual basis; and seven such semi-annual reports were issued for the period October 1961 through March 1965.

Analyses completed, for which results have been reported, are discussed in Section II under descriptive headings. Work currently in progress, which has not reached the stage where results are available, is discussed in Section III. Section IV contains a discussion of the support and service tasks performed for in-house projects and for other VELA UNIFORM participants. Work previously completed and reported is mentioned only as it relates to analyses in progress during this reporting period.

Appendix A is a listing of those organizations receiving SDL data services during this period; and Appendix B contains selected SDL reports which are representative of the types of analyses made by the Seismic Data Laboratory.

II. WORK COMPLETED

A. Seismic Partial Coherency Study

This report presents the results of a preliminary investigation into the application of partial coherency techniques to the problem of processing seismic data. Ultimately, these techniques will be applied to the detection of the presence or absence of unidentified components in seismic noise, determination of filter responses between two time series, and description of seismic noise fields.

A specific application of partial coherencies to seismology would be the modeling of a seismic noise field. If a noise field has only one component propagating across an area, then the output of one seismometer should suffice to predict the output of a second. If there are two components in the field, then two element outputs are required to predict a third. If there are n components, n elements are required to predict the output of one additional element. The methods of partial coherencies can be used to determine when sufficiently many inputs are being used to predict an output. Thus, it will be possible, by using partial coherencies, to determine the number of major noise components present and the minimum number of elements required to study the noise field.

Before the development of a general program, it was necessary to study partial coherence techniques applied to the solution of relatively simple problems under controlled conditions.

The application of power spectra and cross-spectra to determine frequency response functions for simple linear systems, where a single input and output are clearly defined, is well established. Application of these ideas to more complex systems such as the earth where there are many input and output points is not so well known.

Consider the case of a simple linear system with a well-defined single input (excitation) point and single output (response) point. If the input x(t) is a stationary random process with zero mean, then the output y(t) is also a stationary random process with zero mean. Now, if $G_x(f)$ and $G_y(f)$ are the one-sided power spectral density functions, and $G_{xy}(f)$ the cross-power spectral density for the input and output; then the frequency response function for the linear system, H(f) is completely determined by the two relations

$$G_y(f) = |H(f)|^2 \quad G_x(f) \tag{1}$$

$$G_{xy}(f) = H(f)\ G_x(f) \tag{2}$$

A quantity of particular importance in more complicated situations is the <u>coherence function</u> which is defined by

$$\gamma_{xy}^2(f) = \frac{|G_{xy}(f)|^2}{G_x(f)\ G_y(f)} \tag{3}$$

It is easily shown that $0 \leq \gamma_{xy}(f) \leq 1$, and for a linear system, $\gamma^2_{xy}(f) = 1$. Thus, the coherence function may be thought of as a measure of linear relationship in the sense that the function attains a theoretical maximum of unity for all frequencies in a linear system. Therefore, if the coherence function is less than unity, one possible cause might be the lack of complete linear dependence between the input and output.

Another application of coherence functions to single input-single output systems is to determine the effect of measurement noise on frequency response function measurements. The coherence function in this case is

$$\gamma_{xy}^2(f) = \frac{1}{1 + \beta_i + \beta_o + \beta_i \beta_o} \leq 1 \qquad (4)$$

where β_i is the measurement noise to signal ratio at the input and β_o is the corresponding ratio at the output. Hence, if the coherence function is found to be significantly less than unity, one possible cause might be that the measurement noise effects are not negligible and must be taken into account in determining the frequency response function.

Coherence functions are useful aids in the analysis of single input-single output linear systems. However, the area of major application is in the analysis of multiple input-multiple output linear systems which, for example, could represent the response of the earth to internal excitations as measured at several different points. This would be the case when an array of seismic instruments is employed. If it is assumed that the earth has a linear response, and that measurement noise is negligible, then a low coherence function between two points will serve to indicate the presence of other factors which contribute to the output but are not being considered.

In order to investigate partial coherence techniques under controlled conditions, two demonstration cases were developed. These are described briefly below

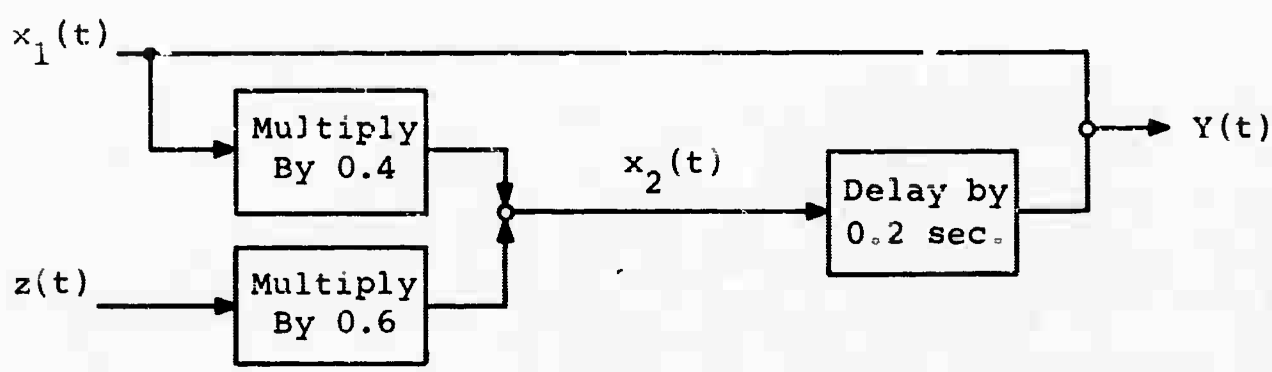
<u>Case 1</u>. Given $x_1(t)$, $x_2(t)$, and $y(t) = a_1x_1(t) + a_2x_2(t-T)$. Determine a_1, a_2, and T in the case where x_1, x_2 are independent and in the case where x_1, x_2 are correlated.

Case 2. Given $x_1(t)$, $x_2(t)$, and

$y(t) = a_1x_1(t) + a_2x_2\ (t-T) + a_3x_3(t)$.

Determine a_1, a_2, T, and the presence of x_3 under various conditions of dependence and independence between x_1, x_2, and x_3.

Consider the linear system sketched below



Two independent seismic sources, $x_1(t)$ and $z(t)$ are combined to form a new process, $x_2(t)$, such that

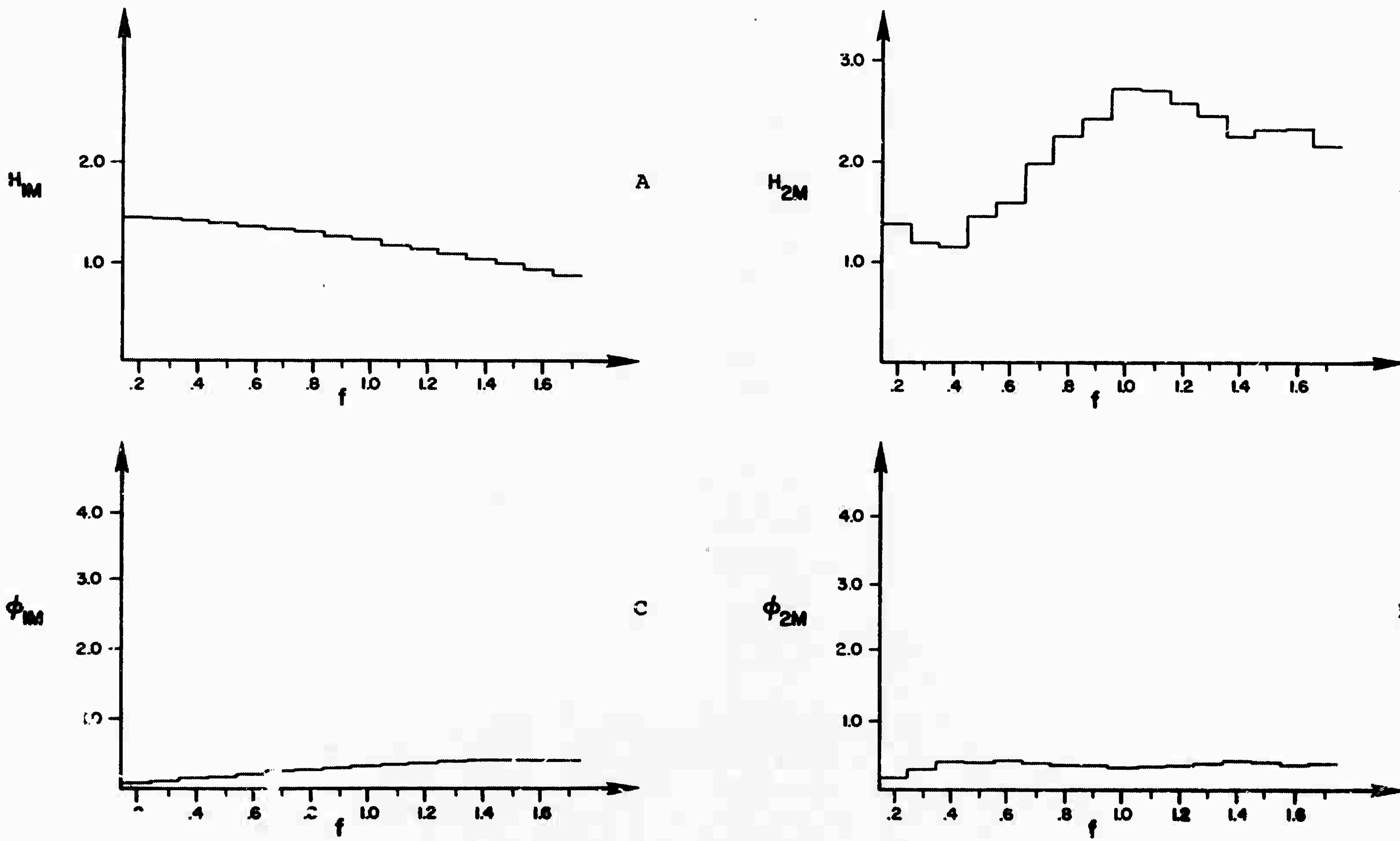
$$x_2(t) = 0.4x_1(t) + 0.6z(t) \tag{5}$$

Secondly, $x_2(t)$ is delayed in time by 0.2 second relative to $x_1(t)$, and finally combined with $x_1(t)$ to form $y(t)$. Thus

$$y(t) = x_1(t) + x_2(\ t - 0.2) \tag{6}$$

If the transfer functions between the two inputs and the output, denoted by $H_{1M}(f)$ and $H_{2M}(f)$, are computed without taking into account the correlation between $x_1(t)$ and $x_2(t)$ completely erroneous results are obtained, as shown in Figure 1. It should be noted that transfer functions are complex quantities in general. They are denoted here by gain and phase variables

$$H(f) = |H(f)|\ e^{j\ \Phi\ (f)} \tag{7}$$



Measured System Response Functions

Figure 1

where $|H(f)|$ is the gain factor and $\phi(f)$ is the phase factor.

The ordinary coherence functions are plotted in Figure 2. If used by themselves to infer the nature of the system being investigated, one would tend to conclude that high measurement noise (i.e. system noise) was present or that nonlinear effects were present. The true nature of the system is exhibited when the partial coherencies are computed, as shown in Figure 3. The fact that all three functions are equal to one over the frequency range indicates the true linear relationships which exist between $x_1(t)$, $x_2(t)$, and $y(t)$.

The demonstration cases investigated through the aid of computer simulation methods illustrate the usefulness of partial coherency techniques in analyzing multiple input-multiple output systems. The fact that correct values of transfer functions and coherence functions are obtained when all inputs are properly taken into account has been numerically illustrated.

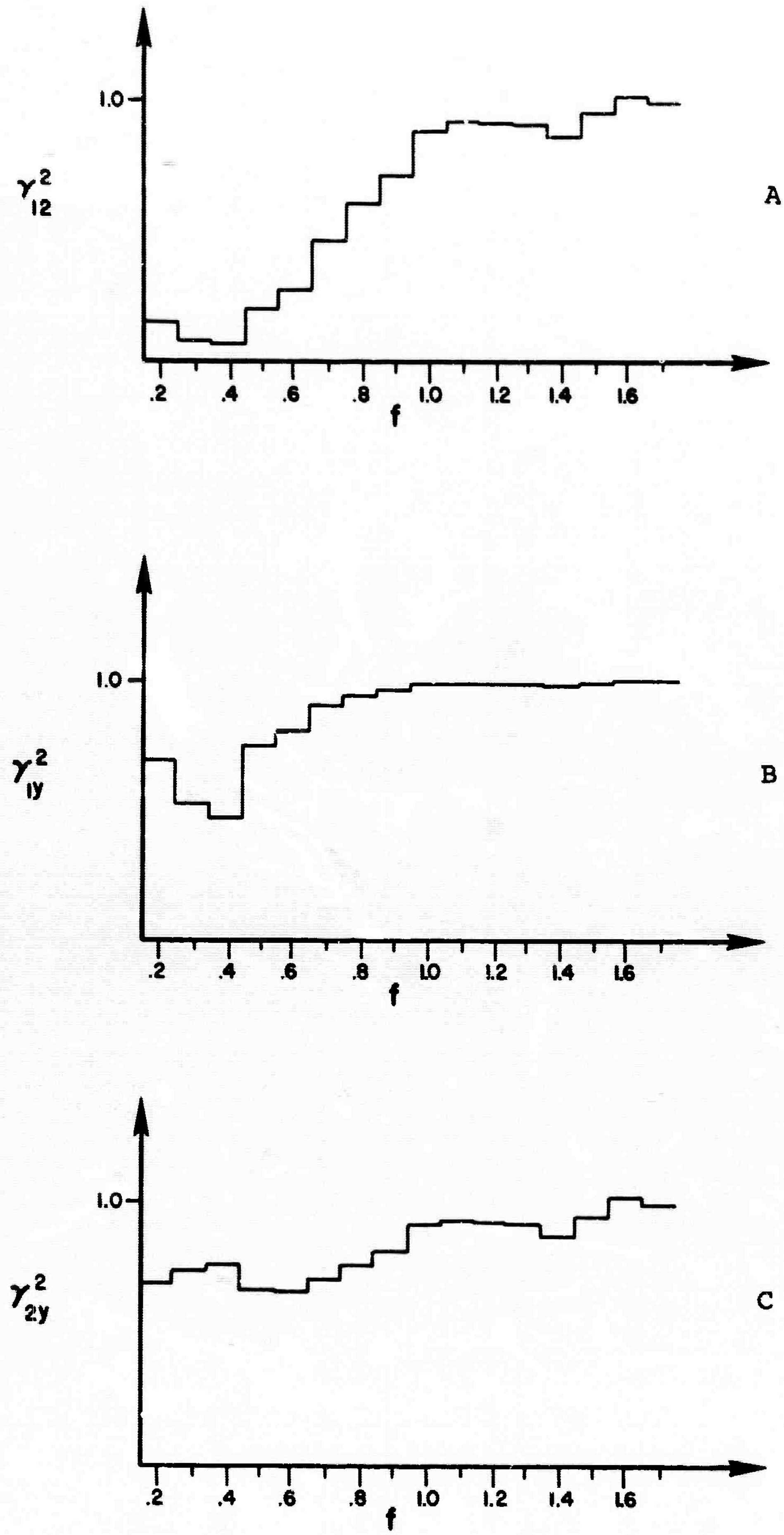
The next step in the investigation will be to use the computational procedures to compute transfer and coherence functions completely from actual data. These can then be compared with the expected results discussed in the report. Questions of statistical accuracy which will be limited by sampling errors in the spectral computations can then be explored. Another area for future study is the trade-offs between statistical accuracy, number of inputs, and computation time.

Finally, a general program must be developed for the multi-input case and applied to the measurement and interpretation of seismic noise in large arrays.

B. Analysis of Arrival Times Across TFSO Extended Array

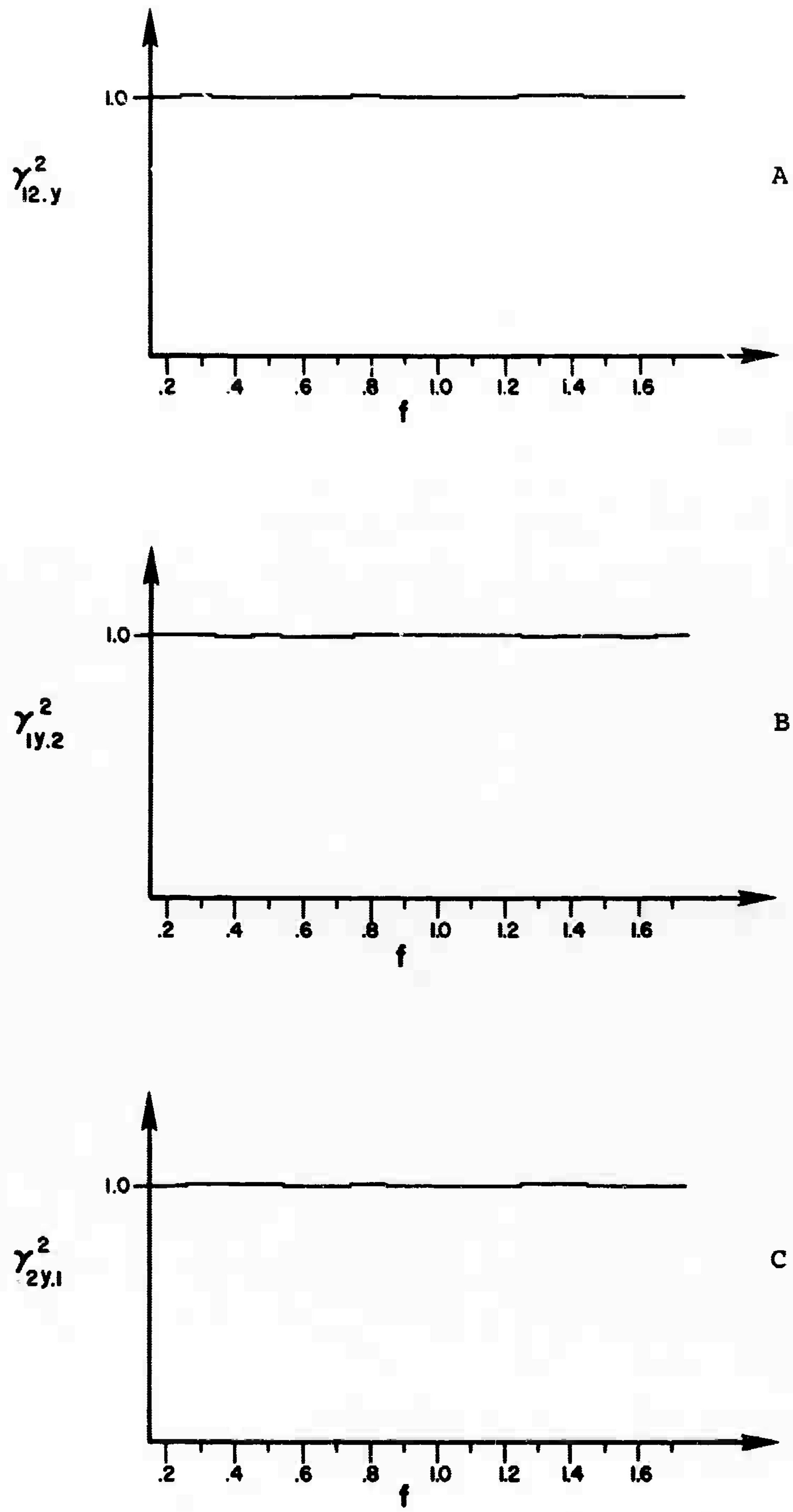
TFSO extended array travel time anomalies discussed in the 15 April 1965 Semi-Annual Technical Summary Report has been extended to include events from six teleseismic epicentral regions northwest of TFSO. The travel time anomalies were measured from films.

Table I shows the mean travel time anomalies relative to the center of TFSO for the eight LRSM sites in the extended array. Some of the events used to measure the Kurile Island anomalies were also used for the Honshu and Kamchatka regions. However, both of these regions include measurements from events not included in the Kurile Island group.



Ordinary Coherence Functions

Figure 2



Partial Coherence Functions

Figure 3

Event Regions	Mariana Is.	Honshu	Kurile Is.	Kamchatka	Rat Is.	Prince Wm. Sound
No.of Events	10	14	46	22	20	12
Min. Range From TFSO (km)	9839	9038	7033	6722	5828	3705
Max. Range From TFSO (km)	10480	9223	9326	7232	6166	3935
Azimuth From TFSO	$293^\circ \pm 4^\circ$	$313^\circ \pm 1^\circ$	$311^\circ \pm 4^\circ$	$319^\circ \pm 2^\circ$	$313^\circ \pm 1^\circ$	$326^\circ \pm 4^\circ$

Travel Time Anomalies (in sec.)

Station	Mariana Is.	Honshu	Kurile Is.	Kamchatka	Rat Is.	Prince Wm. Sound
SG AZ	$-.18 \pm .06$	$-.09 \pm .08$	$-.00 \pm .08$	$+.02 \pm .07$	$-.30 \pm .07$	$-.29 \pm .03$
JR AZ	$+.15 \pm .09$	$-.03 \pm .11$	$+.01 \pm .11$	$+.07 \pm .06$	$-.02 \pm .04$	$-.10 \pm .05$
LG AZ	$-.11 \pm .07$	$+.01 \pm .09$	$-.03 \pm .16$	$+.04 \pm .10$	$-.02 \pm .06$	$-.08 \pm .04$
GE AZ	$-.02 \pm .04$	$-.08 \pm .08$	$-.14 \pm .09$	$-.14 \pm .12$	$-.02 \pm .07$	$-.03 \pm .14$
NL AZ	$-.74 \pm .10$	$-.42 \pm .12$	$-.54 \pm .11$	$-.76 \pm .12$	(moving)	$-1.17 \pm .07$
WO AZ	$+.20 \pm .09$	$+.09 \pm .08$	$+.00 \pm .10$	$+.13 \pm .09$	$+.16 \pm .08$	$-.36 \pm .04$
HR AZ	$+.14 \pm .13$	$+.17 \pm .12$	$+.16 \pm .09$	$+.26 \pm .07$	$+.17 \pm .06$	$+.03 \pm .09$
SN AZ	$-.20 \pm .11$	$-.34 \pm .08$	$-.36 \pm .08$	$-.41 \pm .07$	$-.41 \pm .08$	$-.18 \pm .07$

Travel Time Anomalies at TFSO Extended Array

Table 1

The size of the travel time anomalies do not seem to be consistent for all six regions for any LRSM station. The difference between maximum and minimum travel time anomalies at each station varies from .12 seconds at GE AZ to .75 seconds at NL AZ. The standard deviations in the travel time anomalies are consistent and approximately .10 seconds. Moreover, the standard deviations are approximately independent of the size of the travel time anomaly. The anomalies from the four central regions, which are closest to the same azimuth, are more consistent than results from all six but as yet no obvious functional pattern describing the variation has become evident.

The effect of summing traces in the extended array without some kind of station corrections is shown in Figures 4 and 5.

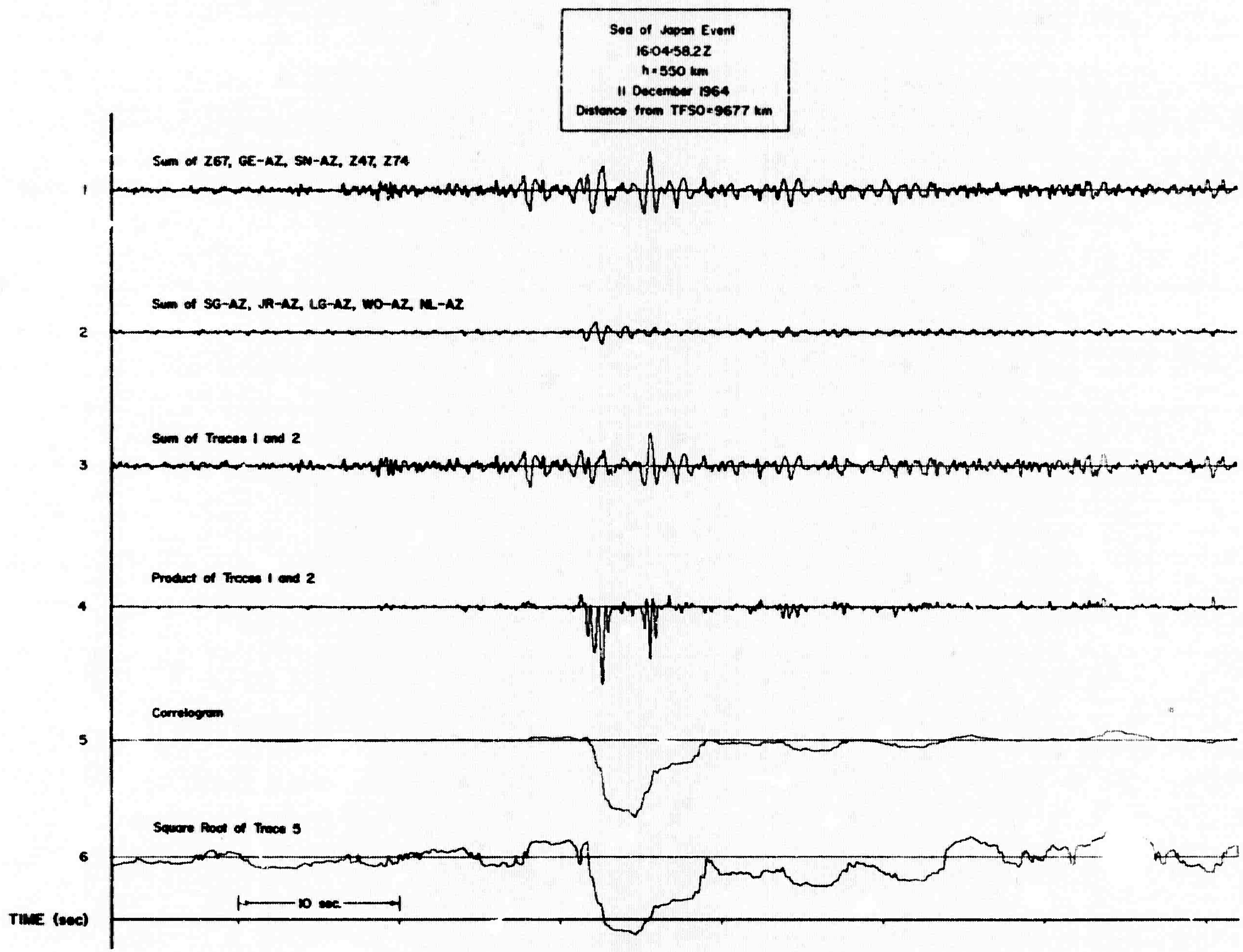
Figure 4 shows the effect of computing a correlogram for this event by aligning the array on velocity only. The first trace is the velocity summation of Z67, GE AZ, SN AZ, Z-47, and Z-74. The second trace is the (velocity) summation of SG AZ, JR AZ, LG AZ, WO AZ, and NL AZ.

Figure 5 shows the correlogram outputs with this event aligned by velocity plus the travel time anomalies appropriate for the Kurile Island earthquakes shown above.

A method has been developed to align events by cross correlations. The array is aligned approximately by velocity. Then the first 20 seconds of P-wave for each trace is cross-correlated with the similar 20 seconds from the Z-47 trace. The shift of the peak of the cross correlation function from the origin indicates the required shift of that trace relative to Z-47. The results using this method are comparable, if not better than those shown in Figure 5, and the method can be used to automate the determination of station corrections.

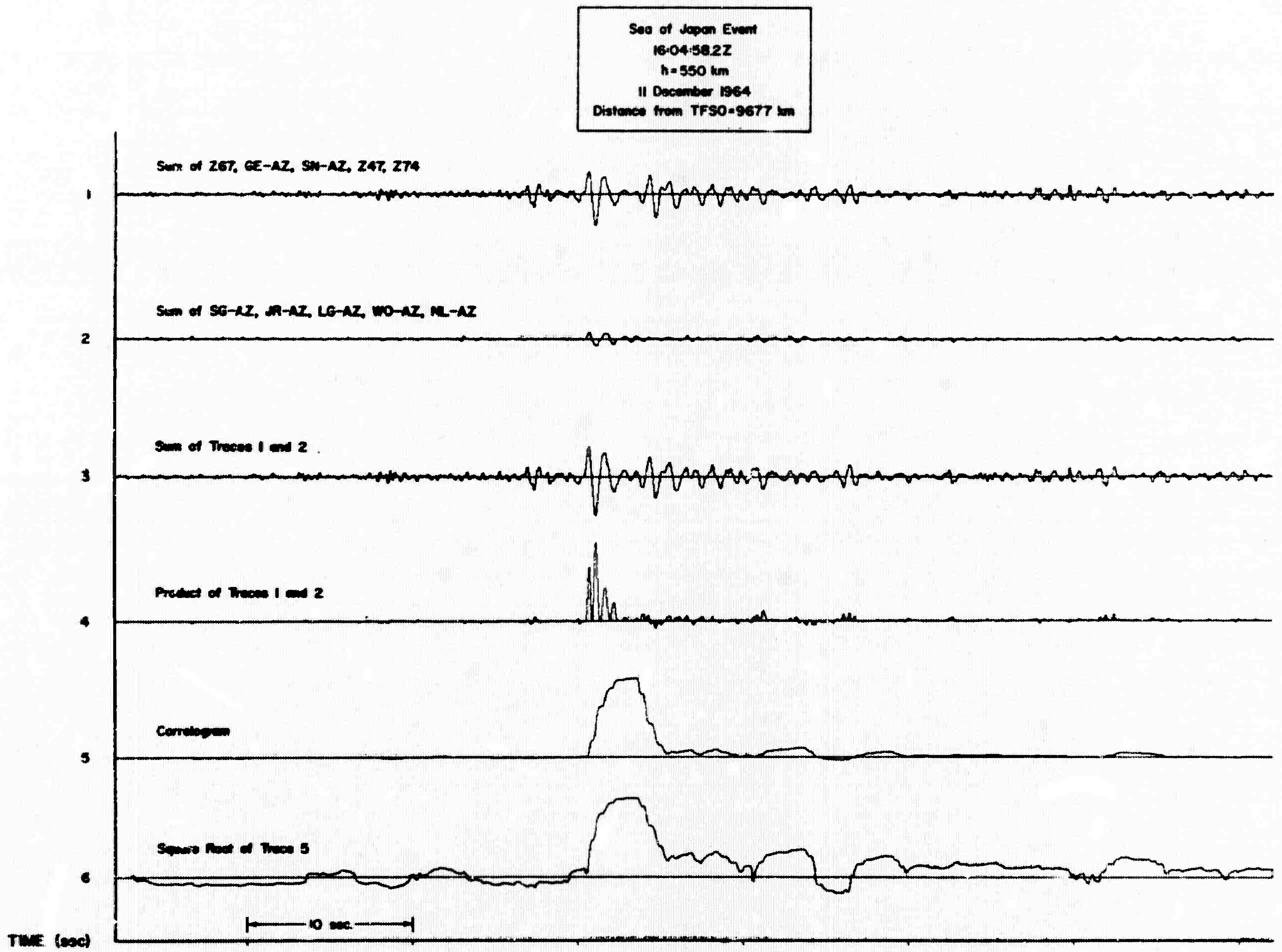
C. Analysis of Seismic Data From WAGTAIL

WAGTAIL was detonated at the Nevada Test Site on 3 March 1965. Thirty-four stations recorded short-period signals and 20 stations recorded long-period signals. It is possible that more stations in the U. S. would have recorded surface waves if it were not for the interference caused by an unidentified earthquake. Thirteen stations showed compressional first motion as defined by the First Motion Criteria (TWG II). The average magnitude was 5.33 and the most



"Correlograms with Array Aligned by Velocity Only"

Figure 4



"Correlograms With Array Aligned by Velocity Plus Travel T'me Anomalies"

Figure 5

distant station recording WAGTAIL was at Oslo, Norway, a distance of about 8,130 kilometers. Table 2 summarizes the measurements made of the principal phases from the WAGTAIL event. Included are the Pn and P arrival times, the maximum amplitudes (A/T) of Pn or P and Pg motion as seen on the short-period vertical instruments, and the maximum amplitudes (A/T) of the Lg phases as measured on the short-period horizontal tangential component. Long-period Love and Rayleigh wave motion are also tabulated in (A/T) form.

D. Computation of Depth of Focus Using pP Arrival Times

The epicenter location program, LOCATE, has been modified to determine depth of focus using pP time intervals. After having read in pP arrival times for an event in the same manner as P, the depth is determined from pP by first computing the distance from the approximate epicenter to all stations reporting pP times; the table of pP-P time interval vs. distance is entered to find the estimated depth of focus for each station reporting pP time; the mean and standard deviation of depth is computed from station depth estimates; finally, epicenter and origin time are computed with depth constrained to the computed value as determined by the prior computations. Upon convergence of the program, the confidence regions are computed as before for latitude, longitude and origin time. In the arrival time listing, the pP and pP-P intervals are printed along with the other information.

E. Analysis of Short-Period Noise and Arrays at Three English Seismological Observatories

This study was made jointly by the VELA Seismological Center (VSC) and the Sei[illegible]c Data Laboratory and resulted in AFTAC Technical Report VU-65-2.

Programs were written and the following data computations made:

1. Five 150 second multichannel data samples were digitized at 20 samples/sec to produce 3000 data points from each channel. The mean and linear trend were removed.
2. High resolution (300 lags) and low resolution (100 lags) power spectra were computed for one channel from each multichannel sample.

Principal Phases
WAGTAIL
3 March 1965
19:13:00.0 Z

Code	Station	Distance (km)	Inst.	Magnification (k) Film X 10	Phase	Observed Travel Time (min)	Observed Travel Time (sec)	Period T (sec)	Maximum Amplitude A/T	TWG II First Motion	Magnitude (m)
MN-NV	Mina, Nevada	240	SPZ	2.80	Pn	00	37.2	0.6	2,700	C	5.73
			SPZ	2.80	Pg			0.5	11,900		
			SPZ	2.60	(PPP)	00	51.1	0.55	4,720		
			SPT	1.92*	Lg			0.75	11,600		
			LPZ	2.50	LR			14.0	614		
			LPT	26.4	LQ			7.0	1,310		
KN-UT	Kanab, Utah	286	SPZ	6.70	Pn	00	42.9	0.65	2,410	C	5.88
			SPZ	6.70	Pg			0.6	7,560		
			SPT	2.29*	Lg			0.8	8,660		
			LPZ	2.89	LR			12.0	566		
SG-AZ	Seligman, Arizona	295	SPZ	8.95	Pn	00	44.3	0.4	700	C	5.35
			SPZ	8.95	P*	00	48.7	0.45	392		
			SPZ	2.47*	Pg			0.45	6,250		
			SPT	2.31*	Lg			0.6	6,803		
			LPZ	15.1	LR			13.0	474		
JR-AZ	Jerome, Arizona	442	SPZ	16.0	Pn	01	03.1	0.6	672	C	5.33
			SPZ		Other phases and Pg clipped on film and tape						
			SPT	4.70*	Lg			0.65	3,400		
			LPZ	1.90	LR			14.0	331		
			LPT	19.5	LQ			6.0	479		
LG-AZ	Long Valley, Arizona	502	SPZ	19.9	Pn	01	10.7	0.6	189	C	5.58
			SPZ	10.0*	Pg			0.8	1,690		
			SPT	18.8	Lg			0.8	1,080		
			LPZ	10.4	LR			14.5	281		
			LPT	10.8	LQ			7.5	(305)		
TFSO	Tonto Forest Observatory, Arizona	530	SPZ-47	33.4*	Pn	01	14.4	0.5	206	C	5.62
			SPZ-47	33.4*	PP	01	21.7	0.5	222		
			SPZ-47	33.4*	P*	01	24.0	0.6	180		
			SPZ-47*	33.4*	PPP	01	28.3	0.7	266		
			SPZ-47	33.4*	Pg			0.85	973		
			LPZ			Clipped on tape					
SN-AZ	Sunflower, Arizona	531	SPZ	17.3	Pn	01	14.1	0.6	215	C	5.63
			SPZ		Pg		Clipped on film and tape.				
			SPT	19.0	Lg			0.9	1,580		
			LPZ	15.7	LR			14.0	298		
			LPT	8.7	LQ			8.0	417		
HR-AZ	Heber, Arizona	543	SPZ	24.0	Pn	01	16.3	0.45	113	C	5.45
			SPZ	24.0	P*	01	26.4	0.65	234		
			SPZ	14.9*	Pg			0.65	913		
			SPT	9.57*	Lg			0.75	1,380		
			LPZ	25.4	LR			14.0	302		
WO-AZ	Winslow, Arizona	545	SPZ	26.4	Pn	01	16.2	0.45	81.9	C	5.19
			SPT	9.93*	Lg			0.85	1,970		
NL2AZ	Naalini, Arizona	591	SPZ	33.4	Pn	01	21.6	0.45	268	C	5.93
			LPZ	8.02	LR			12.5	547		
			LPT	7.85	LQ			9.5	318		
GE-AZ	Globe, Arizona	619	SPZ	48.7	Pn	01	25.3	0.45	82.4	C	5.4[illegible]
			SPZ		Pg		Clipped on film and tape				
			SPT	21.1*	Lg			0.8	835		
			LPZ	5.35	LR			16.0	206		
UBSO	Uinta Basin Observatory, Utah	669	SPZ-10	15.3	Pn	01	33.9	0.9	369	C	6.17
			SPZ-10	15.3	PP	01	39.5	0.95	239		
			SPZ-10	15.3	(PPP)	01	44.3	1.0	167		
			SPZ-10	39.4*	Pg			0.75	485		
			SPN	40.5*	Lg			1.0	1,060		
			LPZ	49.0	LR			14.0	124		
HL2ID	Hailey, Idaho	735	SPZ	61.5	Pn	01	39.4	0.55	10.4	C	4.72
			SPZ	61.5	PP	01	47.8	0.5	74.0		
			SPZ	29.7*	Pg			0.9	575		
			SPT	60.2	Lg			0.9	633		
			LPZ	44.0	LR			14.0	116		
PI2WY	Pinedale, Wyoming	841	SPZ	89.2*	Pn	01	54.2	0.7	99.1		5.90
			SPZ	89.2*	Pg			0.55	136		
			SPT	130*	Lg			1.0	400		
BMSO	Blue Mountain Observatory, Oregon		SPZ-3	45.0	Pn	01	58.2	0.55	10.6		5.03
			SPZ-3	45.0	PP	02	05.8	0.8	45.6		
			SPZ-3	82.3*	Pg			1.1	279		
			SPE	75.3*	Lg			1.05	403		
			LPZ	55.0	LR			14.0	113		
			LPZ	9.5	LQ			(8.0)	(132)		
LC-NM	Las Cruces, New Mexico	1,006	SPZ	157	P	02	14.8	0.8	[illegible].85		4.97
			SPZ	157	PP	02	22.8	0.7	14.2		
			SPZ	157	PPP	02	28.6	0.65	19.5		
			SPZ	37.7*	Pg			1.0	506		
			SPT	164	Lg			1.40	221		
			LPZ	6.80	LR			15.0	234		
RT-NM	Raton, New Mexico	1,041	SPZ	201	(PP)	02	25.0	1.2	19.0		
			SPZ	201	Pg			0.8	169		
			SPT	201	Lg			0.8	180		
			LPZ	14.1	LR			11.5	94.4		
HY-MA	Hysham, Montana	1,239	SPZ	242	P	02	42.0	1.2	19.0		5.13
			SPZ	242	(PP)	02	52.0	0.9	31.8		
			SPT	162	Lg			1.7	117		

Principal Phases
WAGTAIL
3 March 1965
19:13:00.0 Z

Code	Station	Distance (km)	Inst.	Magnification (k) Film X 10	Phase	Observed Travel Time (min)	Observed Travel Time (sec)	Period T (sec)	Maximum Amplitude A/T	TWG II First Motion	Magnitude (m)
FO-TX	Fort Stockton,	1,407	SPZ	410	P	03	(05.[illegible])	(0.8)	(19.3)		5.29
	Texas		SPZ	410	PPP	03	21.0	(0.8)	(14.8)		
			SPZ	410	Pg			(0.95)	31.8		
			SPT	343	Lg			(0.95)	85.0		
WMSO	Wichita Mountain	1,394	SPZ-6	200	P	03	(27.5)	1.35	35.4		5.05
	Observatory, Oklahoma		SPZ-6	1020*	PP	03	38.7	1.2	35.8		
			SPZ-6	1020*	Pg			1.15	73.5		
			SPN	880*	Lg			1.30	63.0		
RY-ND	Ryder,	1,706	SPZ	38.0	P	03	38.0	(0.7)	(22.6)		4.55
	North Dakota		SPZ	38.0	PP	03	48.4	0.7	72.1		
			SPZ	38.0	PPP	03	54.5	0.7	54.1		
			SPT	39.9	(Lg)			1.2	96.6		
GV-TX	Grapevine,	1,796	SPZ		Phases too small to measure						
	Texas		LPZ	14.1	LR			13.0	139		
VO-IO	Vinton,	2,123	SPZ	95.4	P	04	25.6	0.8	100		5.00
	Iowa		SPT	88.5	(Lg)			1.2	38.8		
			LPZ	18.8	LR			13.0	115		
RK-ON	Red Lake,	2,344	SPZ	172	P	04	45.9	0.95	226		[illegible]
	Ontario		SPZ	172	PP	05	09.3	0.8	29.9		
			SPZ	172	PPP	05	18.4	0.8	26.3		
			SPT	172	(Lg)			1.1	18.7		
PU-MS	Purvis,	2,521	SPZ	130*	P	05	06.2	(0.8)	(105)		5.33
	Mississippi										
CPSO	Cumberland Plateau	2,729	SPZ-8	613*	P	05	21.6	0.8	46.9		5.07
	Observatory, Tennessee		LPZ	35.0	LR			16.0	48.3		
BL-WV	Beckley,	3,057	SPZ	53.6	P	05	48.5	0.7	25.6		5.01
	West Virginia		SPZ	53.6	PP	06	37.8	0.7	22.2		
			SPZ	53.6	PcP	09	07.8	0.65	11.4		
BR-PA	Berlin,	3,238	SPZ	118	P	06	03.6	0.95	31.1		5.09
	Pennsylvania		SPZ	118	(PP)	06	(54.2)	0.9	12.9		
			SPZ	118	(PPP)	07	(11.5)	0.9	14.6		
DH-NY	Delhi,	3,544	SPZ	57.3	P	06	27.0	0.65	20.8		5.02
			SPZ	57.3	PcP	09	18.0	0.8	10.9		
			LPZ	14.1	LR			16.0	52.0		
LS-HN	Lisbon,	3,770	SPZ	98.3	P	06	46.4	0.7	12.2		4.79
	New Hampshire		SPZ	98.3	(PP)	08	(02.0)	(0.7)	(10.5)		
HN-ME	Houlton,	4,067	SPZ	54.1	P	07	08.0	0.7	38.0		5.18
	Maine		SPZ	54.1	PcP	09	(31.8)	(0.6)	6.30		
SV2QB	Schefferville,	4,190	SPZ	105	P	07	16.4	0.8	35.0		5.02
	Quebec		LPZ	66.0	LR			12.0	43.0		
AD-IS	Adak Island,	4,941	SPZ	33.6	P	08	12.5	0.7	117		5.67
	Alaska										
OO-NW	Oslo,	8,129	SPZ	106	P	11	31.9	0.85	26.9		5.33
	Norway		SPZ	106	(PP)	14	(24.6)	0.85	5.53		

A/T $m\mu$/sec.
C Compressional
( ) Doubtful values or phases
* Measurements made from playouts

3. After filtering and decimating, geometrically non-redundant cross correlations were computed. These were transformed in frequency and wave number to produce wave-number-frequency (w-n-f) power spectra.
4. Plots of all power spectra and (w-n-f) power spectra were produced, together with plots of the infinite velocity summation response and the transform of the spatial window for the (w-n-f) spectra.

F. Seismic Data Compilation and Retrieval

The purpose of this study was to prepare, from several programs previously written, a program to produce compilation of the seismic activity of the earth by regionalization.

The program has been written and is operational; seismic data for the years 1960 through 1964 has been compiled for one-by-one, two-by-two, and five-by-five degree blocks.

The program has the capability to compute a function of magnitude, F(M), for all events in any given year or years, the function being summed over blocks K by L degrees in size, where K is a divisor of 180 and L is a divisor of 90. The function K(M) is at present simply a count of events, but it can be replaced by, e.g., number of events per unit area, number events smaller or larger than a given magnitude, etc. Also the program can be run, using functions other than a simple count.

III. WORK IN PROGRESS

A. Teleseimic Signal and Noise Correlations at the TFSO Extended Array

The objective of this study is to determine the largest dimensions of a seismic array for which the ordinary array processing of aligning signals and mixing (i.e., velocity filtering) still reinforces the signals and cancels the noise. Velocity filtering tends to enhance signals of the same shape and tends to smear, average, or cancel signals of different shapes. The correlation coefficient, which is the maximum value of the normalized cross correlation function, provides a quantitative measure of the similarity in waveshape between two seismic signals. Plotting the correlation coefficients vs. separation between seismometers will provide a measure of correlation vs. distance over the array, and filtering the seismograms through narrow bandpass filters before correlating will provide a measure of correlation vs. frequency.

For this study, the signals used were P-waves from 10 teleseismic earthquakes recorded over the TFSO extended array. Noise samples used were from these same events just prior to the onset of the signals. The events themselves were chosen for the largest signal-to-noise ratio possible which avoided clipping on the magnetic tapes.

B. Correlogram Analysis from Linear Arrays

Correlogram analysis is a continuing study, testing the British array processing technique. Earthquake data, recorded at 5 to 10 array stations, for the months of May, June, July, August, and December 1963, January, February, and March 1964, have been processed and data for April 1964 are being processed.

C. Dispersion Analysis of Surface Waves from Deep Well Data

In addition to the 10 deep wells previously studied and reported, a study of the seismic noise recorded in one deep well was made. The analysis included estimates of power spectral density, phase angle, and coherency, and the theoretical Rayleigh waves in the structure.

D. Rectilinear Motion Detection (REMODE)

The detection and measurement of linearly polarized particle motion is underway. Various methods for detecting time varying polarized waves are described in the literature. These along with our own ideas are being evaluated in order to improve the detection process. The following questions are being asked:

1. What S/N gain is obtained for strong signals?
2. What is the input S/N threshold for detecting weak signals?
3. How badly is the signal being distorted by the process?

The data for answering these questions experimentally consists of the following:

1. A strong signal with virtually no noise is recorded.

2. The signal Z and R component are added to noise recorded at the same station.
3. The noise level is increased in steps until the signal is not detectable by the process.

The following measurements are manually made using the above experimental data

1. Peak to peak amplitude of the signal plus noise (including the signal alone and noise alone) is taken in the time window of the signal's maximum peak to peak amplitude.
2. These measurements are used to compute the S/N ratio of the unprocessed and processed record. The S/N of unprocessed records is plotted vs. the S/N of processed records. Both of these quantities are based on an average computed from measurements of the signal added to twenty different noise samples at the same preset noise level. The noise level is changed approximately 12 times, sufficiently to draw precise experimental curves.

The results to date have been used to evaluate the method of Shimshoni and Smith, using the scalar correlation coefficient as a gain control. Approximately 6 to 12 db of gain was obtained by the process. The detection threshold was for signal approximately 6 db above the noise.

The same method was evaluated with the modification of rotating the Z and R component to Z' and R' determined so that the components are nearly equal (as contrasted with an initial orbit, R/Z, of .25; R'/Z' = 1.0). This produced an increase in the gain of 6 to 12 db, so that 18 db was obtained by the process for strong signals. Furthermore the detection threshold was pushed back to signals 2 db above the noise.

So far all the results have been obtained on the analog computer. This work is continuing. The testing procedure is being extended to the digital computer and the digital program used to process the Salmon data plus any refinements to it (such as the rotation method previously described) will be similarly evaluated.

E. <u>Automation of Data Processing and Analysis</u>

Preliminary processing of time series data has become relatively standardized at SDL. In particular, operations of filtering, spectral analysis, auto- and cross-correlation, measurements of coherency, instrument response and elementary summing and multiplication of time series are used repeatedly, often many of these operations being carried out on the same set of data. In addition, many standard special purpose analysis programs are now in use and the number of such programs is expanding at a rapid rate.

It is advantageous then to consider combination and automation of these processing and analysis methods, especially those that have already become standardized or may reasonably be standardized in their function. In particular, generalized multi-purpose chain programs consisting of several specialized processing and analysis programs can serve to combine these often lengthly procedures and to thereby increase the efficiency of data processing to the point where more complicated operations become feasible.

A system program FLAP (FORTRAN Controlled Linkage of Associated Programs) has successfully been designed. Basically, the system functions as a subroutine control system which allows a FORTRAN program (executive program) to call and execute programs in the same manner as subroutines. The system fulfills all the requirements outlined above with added features of flexibility inherent in a purely FORTRAN system. In particular, digital operations (in the FORTRAN language) may be programmed between calls to the individual programs. This results in optimal interfacing between the various special programs.

A few chain systems involving seismic wave analysis and processing are now in use and many others are in various stages of completion. Such standardized package programs (chains) provide well defined, processed data with a minimum of time and effort.

F. Recursive Numerical Filters

A set of programs which can be used to model analog filters on the digital computer are now operational. Certain problems still exist in the use of these programs, but sufficient checks are built in so that the inherent errors should not be a serious limitation in practice.

Seismic systems have been modeled. The major emphasis, however, has been on the design of low- and band-pass filters.

For these, the program limitations have been well bounded.

Stable low-pass filters have been designed with roughly the following limits: low-pass band width of 0.10 cps. with 24 db slopes, 0.30 cps. with 36 db slopes, 1.0 cps with 60 db slopes, and 8.0 cps. with 120 db slopes.

The band-pass filters are designed by first generating the coefficients of the low-pass filter which is half as wide as the requested band-pass filter, and then, using the coefficients, a new set of coefficients is computed by shifting the low-pass center frequency from 0.00 cps to the requested center frequency. To date, no stable filter has been made unstable by shifting.

At present, it is felt that no further research type work should be done on the program. However, as the program now exists in independent parts, the present plan is to put the parts together and introduce input flexibility so that the program may be presented as a package to the general user.

G. <u>Modification of LOCATE Program for Event Epicenter Determination using Reported P Arrival Times from 3 or 4 Stations</u>.

The event location program, LOCATE, has been revised to accept data from a minimum of three stations. With this small number of stations, the standard errors and confidence regions can not be computed as they are normally done when data from more than five stations are used. Moreover, to operate on data from three stations, two of the four normal variables are constrained to the input values; these are the origin time and depth of focus, and are taken from the USC & GS listing which are assumed to be correct for each event.

In an operational system, the origin time and depth would not be known; in which case, the depth would be assumed to be zero or some other convenient value.

A preliminary study has been made to test the precision of epicenters based on 3 and 4 station data.

Only relatively large magnitude events were used, with data from a very few falling in the low magnitude four range. The results were studied in terms of the computed azimuth and distance of each event from the epicenter determined, using data from a large number of well distributed stations, as reported by the USC & GS.

The attached Table 3 lists the epicenter shifts in kilometers and azimuth along with the standard deviations and the measurement of dispersion.

We can conclude from this limited data that an epicenter based on data from three or four stations is valid within approximately 200 kilometers. Although this precision is obviously not good enough to help us make a practical decision regarding on-site inspection, it is good enough as a first approximation on which we may base corrections and techniques for precise beam steering and a precise epicenter determination based on data from many stations.

The tripartite array TFO, UBO, and BMO is roughly within the same geologic provice while WMO in Oklahoma clearly causes the array TFO, UBO, and BMO to overlap two distinct provinces. This fact may explain in part the apparent slight improvement of epicenter computations based on the first array over those based on the second array. The use of all four stations appears to improve the precision even more, but probably not enough to improve appreciably the choice of arrival-time corrections needed for beam steering and precise epicenter determination. The principal advantage of four stations is provide redundancy in the event that data from one of the stations is unusable.

Further work on this problem should include similar studies of events from other regions of the world, the effect of magnitude or signal-to-noise ratio on epicenter determination, and the effect of making station travel time corrections.

H. Large Aperture Seismic Array (LASA) Data Processing

Studies are being made on the additional electronic equipment and the new data processing requirements which the SDL will need in order to process the LASA data.

Equipment ordered includes a 604 magnetic tape drive and controller which will read LASA data generated at 800 bpi, a

Location	Total Number of Events	Discarded	Average Azimuth	Average Distance (km)
		Three Stations (TFO, UBO, WMO)		
N. Kuriles	24	2	$266^\circ \pm 20^\circ$	242 ± 64
S. Kuriles	17	2	$273^\circ \pm 19^\circ$	132 ± 32
Alaska/Aleutians	16	0	$106^\circ \pm 24^\circ$	144 ± 110
	4	0	$290^\circ \pm 28^\circ$	192 ± 56
		Three Stations (TFO, UBO, BMO)		
N. Kuriles	24	0	$100^\circ \pm 68^\circ$	135 ± 58
S. Kuriles	14	4	$271^\circ \pm 20^\circ$	133 ± 59
Alaska/Aleutians	13	1	$75^\circ \pm 38^\circ$	84 ± 43
	5	0	$328^\circ \pm 11^\circ$	138 ± 53
		Four Stations (TFO, UBO, BMO, WMO)		
N. Kuriles	24	1	$304^\circ \pm 30^\circ$	161 ± 50
S. Kuriles	16	1	$274^\circ \pm 17^\circ$	130 ± 27
Alaska/Aleutians	11	1	$101^\circ \pm 16^\circ$	53 ± 24
	6	1	$302^\circ \pm 34^\circ$	59 ± 35

TABLE OF COMPUTED ERRORS

TABLE 3

200 million bit disk file which will afford rapid access to the LASA data. Still under consideration are several types of digital-to-analog subsystems for data processing.

Two digital computer programs have been written. One program, written and checked out for the 160-A, will read LASA data and transmit it from the 160-A to the 1604 via the satellite hardware. The other program, written for array processing, receives the data from the 160-A, phases the data for a specific angle, velocity, starting time, and time interval, and outputs a tape containing the phased sum of each of the 21 subarrays.

A maximum of 20 data points can be lagged across each subarray. Multiple input and output tapes are allowed and any amount of input data can be processed. The array configuration can be varied. It is estimated that processing will take 4.5 times real time.

IV. SUPPORT AND SERVICE TASKS

As part of the contract work-statement, the SDL provided one or more of the following support and service functions for AFTAC and other VELA participants:

- copies of 16 and 35 mm film
- copies of existing composite analog tapes
- composite analog tapes of special events
- use of 1604 computer for checking out new programs or running production programs
- copies of digital programs
- digitized data in standard formats or special formats for use on computers other than the 1604
- running SDL production programs, such as power spectral density, and array processing on specified data
- digital x - y plots of power spectra or digitized data
- signal reproduction booklets

In addition, visiting scientists utilized SDL facilities to study data and exchange information with SDL personnel.

A. Data Library

The Data Library contains 3600 digitized seismograms, 106 digital computer programs, and 212 composite analog magnetic tapes, all available for use by the VELA-UNIFORM program.

The following additions were made during this report period:

1. Digital Seismograms - 554, including:

   - deep well noise from EK NV, OR FL, and AP OK
   - noise samples on a new slow-speed tape transport
   - long and short period data from BILBY, SHOAL, and the FALLON earthquake
   - noise data from one of the LASA subarrays
   - many earthquakes recorded at the VELA observatories and the TFO extended array

2. Digital Programs - 4, including:

   - POLES1A2 - This program generates the complex plane poles and normalizing constant for use in characterizing the denominator and numerator, respectively, of a LaPlace transform. At present, the subroutine creates only Butterworth or Chebyschev poles. However, it is constructed to be easily expanded to include other special functions.

   - RESPOND - For given wave number, this program computes the response of an array of seismometers along a specified azimuth.

   - DCONVOL1 - To remove the response in a seismogram due to the inherent filter characteristics of the seismometer, filter, velocity transducer, and galvanometer. The routine removes the response of one instrument at a time, using the filter characteristics of that instrument. Successive passes through the routine with different filter characteristics will remove all the undesired responses.

   - LAPINV - Given a function of the complex variable s, and an array of the independent variable time, this program generates the time function for each of the time values indicated.

In addition, modifications were made to the following programs:

a. The LOCATE program has been modified to provide the option of computing depth of focus from pP arrival times, and also to locate events using 3 or more stations, instead of a minimum of 6.

b. The COLLATE program has been modified to run from the normal epicenter tapes instead of a special merged tape as it required before. This modification increases the efficiency of the program and reduces the running time by a factor of 10.

c. The DEPTHMAG program has the following added features:

   (1) ability to retrieve from any one of four differently formated tapes.
   (2) ability to save all card images retrieved.
   (3) ability to specify retrieval criteria relative to recording stations, data source codes, and distance and azimuth.

3. <u>Analog Composite Tapes</u> - 20, including:

a. Made by Seismic Data Laboratory

   -WAGTAIL
   -Special composites made for AFTAC, the Air Force Cambridge Research Laboratory, Texas Instruments, Inc., and General Atronics Corporation

b. Made by the Geotechnical Corporation

   -TURF
   -STURGEON
   -OCONTO
   -HOOK
   -TORNILLO

4. <u>Other Data Available to VELA Participants</u>

The following data was added to our magnetic tape storage:

- U. S. Coast and Geodetic Survey epicenters from March 1965 to May 1965
- Earthquake Bulletin Data from the LRSM stations (November 1964 to February 1965)
- Earthquake Bulletin Data from the VELA observatories (December 1964)

B. Data Compression

This is a continuing routine operation, and production is maintained at the level needed to meet the requirements of the field operations (LRSM teams and U. S. observatories) and the Seismic Data Laboratory.

C. Equipment Modifications

No modifications, other than those discussed under III-H (LASA planning), were made during this report period.

D. Automated Bulletin Process

During this report period, the ABP digital program was run for the January, February and March 1965 earthquakes bulletins issued by the Geotechnical Corporation.

The program is being continuously modified to associate and identify a greater percentage of phase arrivals.

ORGANIZATIONS RECEIVING SDL DATA SERVICES

APRIL 1965 - JUNE 1965

AFCRL
Boston College
Engineering Physics
General Atronics Corp.
Geotechnical Corp.
Institute for Defense Analysis
International Seismological Research Centre(Scotland)
Lamont Geophysical Observatory
Lincoln Laboratories
Penn State University
Princeton University
St. Louis University
Texas Instruments, Inc.
U.S. Coast and Geodetic Survey
Vitro Corp.

APPENDIX A

SELECTED REPORTS ISSUED

Booker, A. H.; A statistical discriminator; 22 November 1962

Booker, A. H.; Estimation of network capability; 20 January 1964

Booker, A. H.; Parameter dependence of integrated seismic phases; 25 May 1965

Bradford, J. C.; Enochson, L. D.[1]; and Thrall, G. P.[1]; Seismic partial coherency; 28 April 1965

Claerbout, J. F.; Detection of P waves from weak sources at great distances; 13 September 1963

Dean, W. C.; Inverse filtering of seismic signals; 1 August 1962

Dean, W. C.; Correlograms of MISSISSIPPI from orthogonal filters; 1 March 1963

Flinn, E. A.; Confidence regions and error determinations for seismic event location; 24 April 1964

Flinn, E. A.; Engdahl, E. R.[2]; A proposed basis for geographical and seismic regionalization; 9 March 1964

Martinek, J.; Thielman, H.P.; Special sphere and circle theorems for the general biharmonic field; 8 July 1963

Martinek, J.; Thielman, H. P.; Special sphere and circle theorems for the general biharmonic equation - interior and exterior problems; 11 December 1963

Martinek, J.; Thielman, H. P.; Propagation of waves from a spherical cavity into concentric spheres; 13 March 1964

Martinek, J.; Thielman, H. P.; Methods for obtaining new solutions to the harmonic and wave equations; 30 April 1964

1 Measurement Analysis Corp.

2 U.S. Coast & Geodetic Survey

APPENDIX B

Mims, C. H.; A sum-of-squares method of seismic phase identification; 27 November 1962

Mims, C. H.; Detectability of first motion; 15 August 1963

Mitronovas, W.; Identification of nuclear explosions on the shape of initial P-phase for teleseismic events; 28 August 1964

Mitronovas, W.; Identification of nuclear explosions using ratios of smoothed and combined seismic phases; 28 June 1963

Pilotte, F. F.[1]; Flinn, E. A.; A preliminary evaluation of a method for linear array processing; 31 January 1964

Sax, R. L.; Attenuation of head waves as a function of frequency and distance; 28 February 1963

Sax, R. L.; Hartenberger, R. A.; Theoretical estimation of the signal-to-noise ratio as a function of depth; 3 April 1963

Sax, R. L.; Hartenberger, R. A.; Theoretical prediction of seismic noise in a deep borehole; 24 September 1963

Sax, R. L., and Hartenberger, R. A.; Seismic noise attenuation in unconsolidated material; 28 August 1964

Thielman, H. P., and Sax, R. L.; Relation giving the phase velocity in terms of the group velocity; 28 September 1962

Van Nostrand, R.,; Synthetic earthquake seismograms for teleseismic distances; 14 May 1964

Van Nostrand, R., and Helterbrand, W.[1]; A comparative study of the SHOAL event; 29 August 1964

[1]AFTAC

Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) UED Earth Sciences Division Teledyne, Inc. Alexandria, Va.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
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4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Quarterly Summary, April 1965 - June 1965

5. AUTHOR(S) (Last name, first name, initial)
Van Nostrand, Robert G.
Project Scientist

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
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10. AVAILABILITY/LIMITATION NOTICES
Qualified users may request copies of this document from DDC.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Advanced Research Projects Agency Nuclear Test Detection Office Washington, D. C.

13. ABSTRACT This report discusses the work performed for the period April 1965 through June 1965, and is primarily concerned with seismic research activities leading to the detection and identification of nuclear explosions as distinguished from earthquake phenomena. Also discussed are the data services performed for other participants in the VELA UNIFORM Project.

A great part of the work was concerned with large aperture seismic array data processing techniques, such as the measurement of seismic travel time anomalies across the Tonto Forest Seismological Observatory extended array and teleseismic signal and noise correlations at the extended array. Other work was concerned with locating the site of a seismic event and determining the depth at which the event took place, using as the interpretation tool a digital program written for machine processing of pertinent data.

Also, various studies, such as linear array correlogram analysis, rectilinear motion detection and recursive numerical filters, were concerned with means of filtering noise from seismic records in order that the signals from nuclear explosions and earthquakes could be detected and analyzed.

DD FORM 1 JAN 64 1473

Unclassified
Security Classification

Attachment 1

Unclassified
Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Seismic Data Laboratory-Quarterly Tech. Summary						
VELA UNIFORM Project						
Seismic Data Analysis						
Depth of Focus						
Partial Coherency						
Short-Period Seismic Noise						
Dispersion of Surface Waves						
Recursive Numerical Filters						
Seismic Arrays						
Arrival Time Anomalies, Seismic						
Large Aperture Seismic Array						

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GPO 886-551
Attachment 1

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